

## BISCAYNE BAY CONCEPTUAL ECOLOGICAL MODEL

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**Abstract:** Biscayne Bay is a naturally clear-water bay that spans the length of Miami-Dade County, Florida, USA. It is bordered on the east by barrier islands that include Miami Beach and is an almost completely urban bay in the north and a relatively natural bay in the south. Planned water management changes in the next few years may decrease freshwater flows to the bay from present sources, while offering reclaimed wastewater in return. In addition, a project is planned to restore the former diffuse freshwater flow to the bay through many small creeks crossing coastal wetlands by redistributing the water that now flows into the bay through several large canals. To guide a science-based, adaptive-management approach to water-management planning, a conceptual ecological model of Biscayne Bay was developed based upon a series of open workshops involving researchers familiar with Biscayne Bay. The CEM model relates ecological attributes of the bay to outside forcing functions, identified as water management, watershed development, and sea-level rise. The model depicts the effects of these forcing functions on the ecological attributes of the bay through four stressors. The hypothesized pathways of these effects include salinity patterns, water quality, sediment contaminant concentrations, and physical impacts. Major research questions were identified with regard to uncertainties explicit in the model. The issues addressed include, for example (1) the quantitative relationship between upstream water management, rainfall, and flow into Biscayne Bay; (2) the salinity gradient required to restore the historical estuarine fish community; (3) the potential effect of freshwater inputs on benthic habitats; (4) the effect of introduced nutrient and contaminant loads, including the effects of reclaimed wastewater.

**Key Words:** Biscayne Bay, seagrass, dolphins, manatees, fish, pink shrimp, water quality, coastal wetlands, freshwater inflow

### BACKGROUND

Biscayne Bay (Figure 1) is a naturally clear-water bay with tropically enriched flora and fauna. Prior to the development of Miami-Dade County, Florida, USA, much of the bay was bordered by mangroves and, otherwise, with herbaceous wetlands. The bay

was once connected to the Greater Everglades ecosystem hydrologically through tributaries, sloughs, and ground-water flow. It possessed not only a marine habitat and fauna but also a substantial area of estuarine habitat and associated fauna. Because of the bay's shallow depths and naturally clear waters, its productivity is largely benthic-based (Roessler and Beardsley

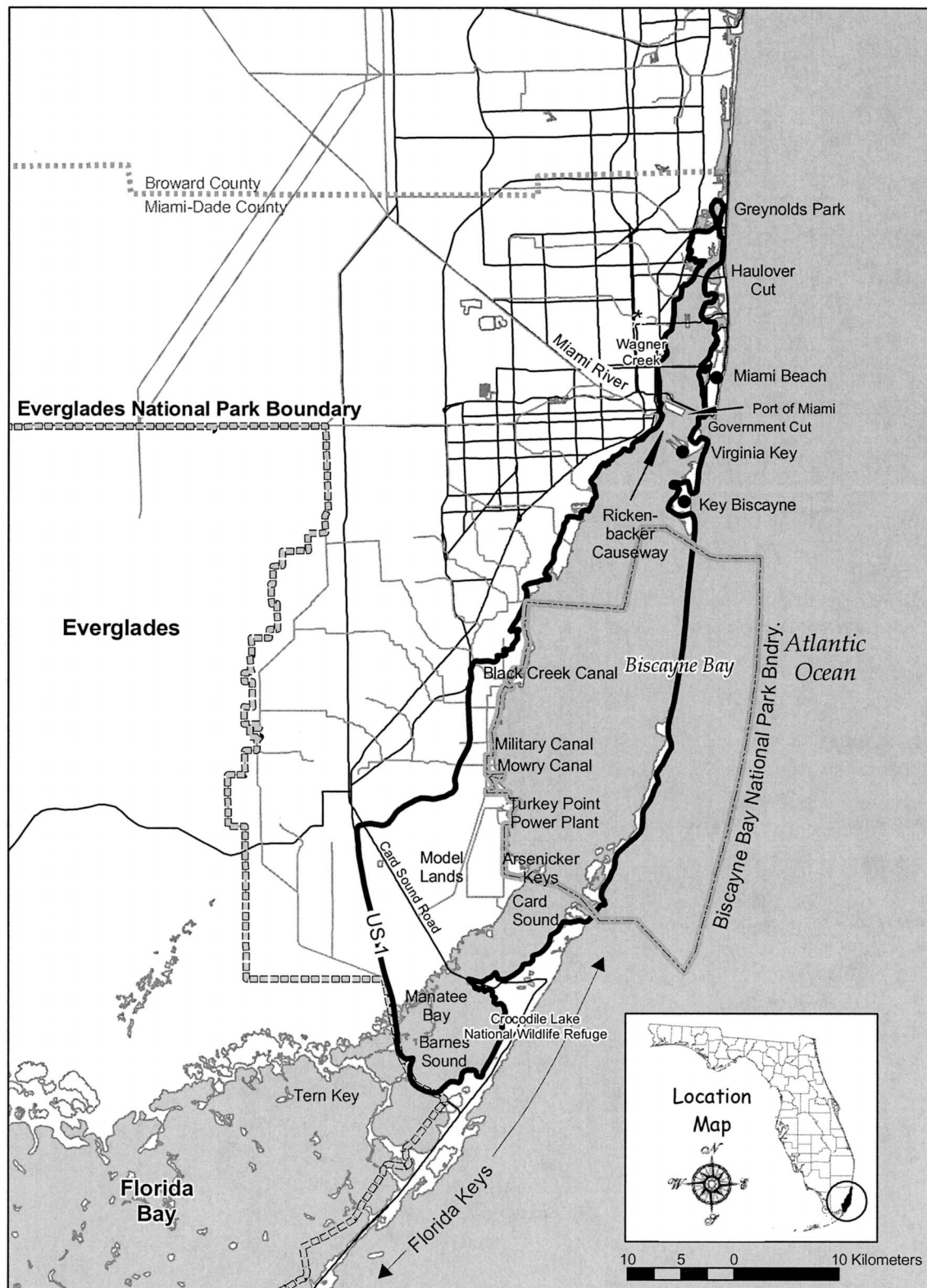


Figure 1. Boundary of the Biscayne Bay Conceptual Ecological Model.

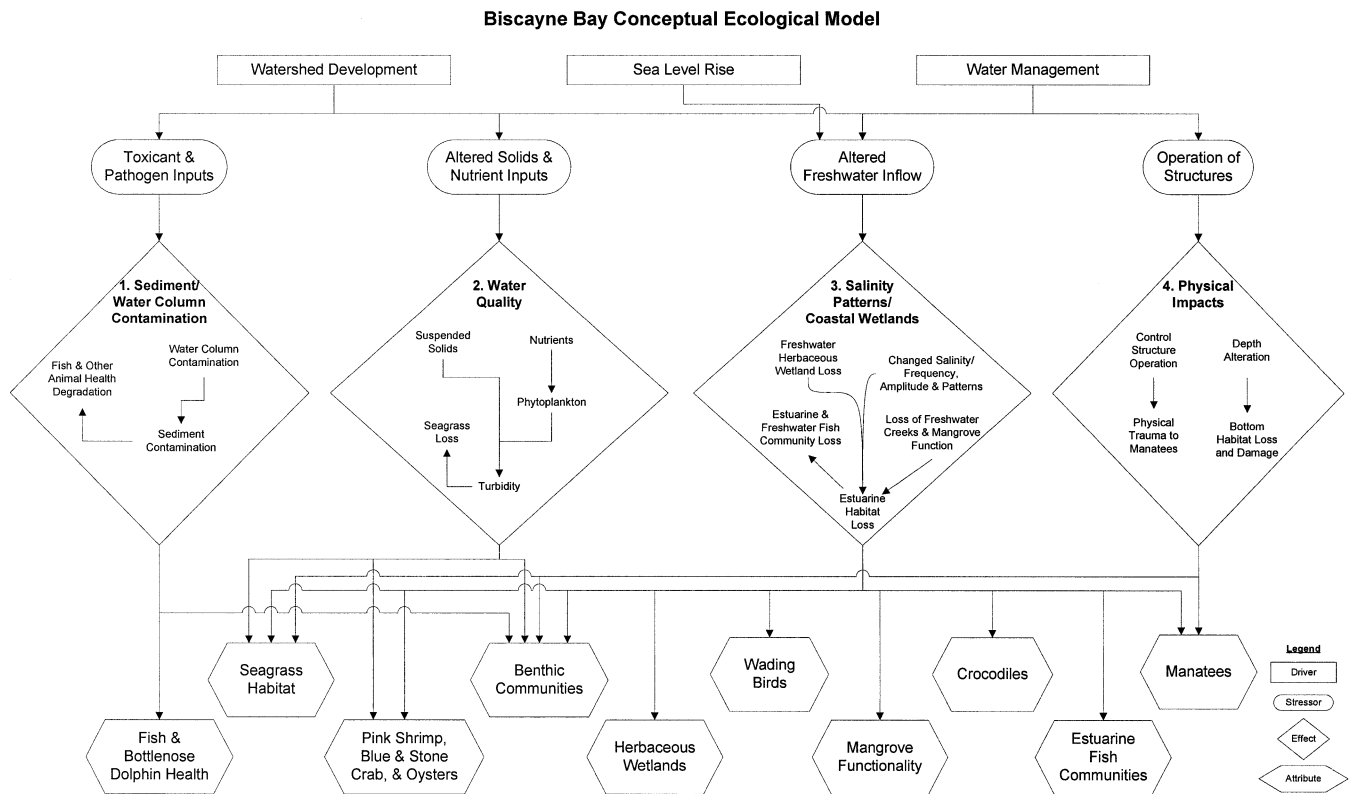


Figure 2. Biscayne Bay Conceptual Ecological Model Diagram.

1974). Benthic communities in the central and southern bay (i.e., south of the Rickenbacker Causeway) consist of several species of seagrasses, a mix of soft and hard corals, attached macroalgae and sponges, and coral-algal bank fringes that alternate in dominance in different areas. Benthic communities in northern Biscayne Bay are dominated by seagrasses intermixed in some cases with calcareous green algae. Parts of the bay are afforded various levels of state or federal protection, being designated or contained within Miami-Dade County Aquatic Park, Florida Aquatic Preserve, Outstanding Florida Water, Outstanding National Resource Water, Florida Surface Water Improvement and Management Priority Water Body, Biscayne National Park, Florida Keys National Marine Sanctuary, and Crocodile Lake National Wildlife Refuge.

Biscayne Bay is one of several south Florida estuaries that will be affected by the Comprehensive Everglades Restoration Plan (CERP) and its 68 individual projects. The selected plan, as described in the 1999 document (USACE and SFWMD 1999), contains provisions that will affect the sources, amount, and therefore quantity and quality of fresh water that Biscayne Bay receives, as well as the timing and location of flow. The specific projects likely to affect the bay most directly are the Biscayne Bay Coastal Wetlands Project, the C-111 Spreader Project, the South Dade Waste

Water Reuse Project, the L31-N Seepage Management Project, and Lake Belt Storage Projects. The Coastal Wetlands Project has the objective of restoring the historic water supply patterns through wetlands to the southern Biscayne Bay. Wastewater reuse has the potential to affect bay water quality. The remaining projects listed all directly affect the amount of fresh water available to Biscayne Bay.

To guide a science-based, adaptive-management approach to water-management planning, a conceptual ecological model of Biscayne Bay was developed based upon a series of open workshops involving researchers familiar with Biscayne Bay. Since the adaptive management process for CERP is the context in which this conceptual model was developed and will be used, the emphasis of the Biscayne Bay CEM is on the relationship between the bay ecology and the mainland shoreline and freshwater sources.

#### EXTERNAL DRIVERS AND ECOLOGICAL STRESSORS

In the Biscayne Bay Conceptual Ecological Model (Figure 2), the two principal drivers applicable to the Comprehensive Everglades Restoration Plan (CERP) are watershed development and water management. They exert their effects through four principal stressors

ors: toxicant and pathogen inputs, altered solids and nutrient inputs, altered freshwater inflow, and operation of physical structures, particularly water-control structures and maintenance of infrastructure. Altered freshwater flow is the stressor that CERP will most directly affect and includes flow volume, velocity, timing and spatial distribution. CERP may indirectly affect the input of solids, nutrients, toxicants, and pathogens.

Construction of the major canals through the Everglades and dredging of natural tributaries and transverse glades that carried fresh water to Biscayne Bay resulted in lowered regional and coastal water tables (Parker *et al.* 1955), reduced water storage in the watershed, decreased ground-water flow to the bay, and the elimination of many tributaries. Drainage of the watershed greatly affected the natural salinity gradients and ecotones from the Everglades through coastal wetlands and tidal creeks into the bay, and reduced or eliminated critical estuarine habitat for bay species requiring low-to-moderate salinity waters. In addition, constructed drainage systems result in pulsed, point-source discharge degrading estuarine habitat near canal mouths by creating biologically damaging zones of bottom scouring and rapid salinity fluctuations. Departures from natural salinity patterns are ecologically damaging to many species because salt concentration affects growth, survival, reproduction, and other critical physiological processes in both plants and animals (see, for example, Kinne [1971]). The general lowering of the water table on the east-coast ridge and diversion of both surface and ground water into canals has degraded not only estuarine habitats within the bay, but also adjacent coastal wetland communities, including herbaceous freshwater marshes and coastal mangrove wetlands that were once functionally connected to the estuarine habitats. The few coastal tropical hammocks that remain have also been detrimentally affected by the lowered water table (M. Roessler, pers. comm.).

The bay has also been significantly affected by the watershed development made possible by water management (Alleman *et al.* 1995). Before drainage of the watershed, urban and agricultural development was restricted to the highest ground along the Atlantic Coastal Ridge, consisting of hammocks and pinelands (University of Miami and SFWMD 1995). As land was drained, development encroached into lower lands and former wetlands. Today, most new development is occurring in former wetlands.

Development has had many detrimental consequences. The continued loss of open, pervious land increases stormwater runoff velocity and pollutant loads and reduces the quantity of water storage in the watershed. Other dramatic changes occurred in north-

ern Biscayne Bay as a result of dredging and filling. Bottom dredging resulted in the loss of seagrass beds in northern Biscayne Bay and has affected the stability of bay sediments and the capacity to assimilate nutrients and trap particulates. Stormwater runoff from urban development has increased the bay's exposure to contaminants and excessive nutrients. At the same time, the filling and destruction of coastal wetlands has eliminated natural filtering capacity. The dredging of inlets at Haulover and Government Cuts significantly increased salinity in northern Biscayne Bay (Wanless 1969, Wanless *et al.* 1984), changing much of it from an estuarine to a more marine system.

Biscayne Bay's water quality has improved substantially in the past 30 years because of the elimination of direct discharge of sewage into the bay and other pollutant-control measures (McNulty 1970, Alleman *et al.* 1995, DERM 2005a). Parts of North Biscayne Bay now support substantial seagrass beds. Extensive seagrass beds have always been characteristic of South Biscayne Bay. In recognition of its exceptional values, the State of Florida has designated the bay and its natural tributaries as Outstanding Florida Waters, and as such, they receive the highest level of state protection from degradation. Present water quality generally meets or exceeds federal, state, and local standards for recreational use and propagation of fish and wildlife. Nonetheless, the bay still receives dissolved nutrients, trace metals, organic chemicals, and suspended sediments via stormwater runoff, sewage overflows, discharges from industrial facilities or vessels, and canal discharges. Canal water typically has lower dissolved oxygen and clarity and higher concentrations of contaminants than receiving waters of the bay.

## ECOLOGICAL ATTRIBUTES

Ecological attributes of the overall health of the Biscayne Bay ecosystem include four types of habitat: seagrass meadows, mangrove forests, herbaceous wetlands, and benthic faunal communities (both soft bottom and hard bottom). Ecological attributes that have been defined because of their special relevance and utility for monitoring and reporting the state of the bay include pink shrimp (*Farfantepenaeus duorarum* Burkenroad), blue crabs (*Callinectes sapidus* Rathbun), stone crabs (*Menippe mercenaria* Say), oysters, estuarine fish communities, fish and bottlenose dolphin (*Tursiops truncatus* Montagu) health, crocodiles (*Crocodylus acutus* Cuvier), West Indian manatees (*Trichechus manatus latirostris* Linnaeus), and wading birds.



## Seagrass Habitat

Large areas of the bay bottom support seagrass communities because sediment depth and nutrients are sufficient, water depths are shallow, and water clarity is high. Seagrass has been documented to cover up to 64% of the bay bottom (DERM 1985). There is very little area of bare bottom with sufficient sediment to support seagrass except where there has been a physical disturbance such as dredging. Seagrass beds function as vital habitat to support critical life stages of a variety of ecologically important and commercially or recreationally valuable species. At least seven species of seagrasses occur in Biscayne Bay: turtle grass (*Thalassia testudinum* Banks & Soland. ex Koenig), shoal grass (*Halodule wrightii* Aschers.), manatee grass (*Syringodium filiforme* Kuetz.), three species of *Halophila*, including *H. johnsonii* (Eiseman), which is a federally-listed protected species, and *Ruppia maritima* (Linnaeus). Distribution of seagrass species is generally related to water clarity and quality, substrate, salinity levels, and variability. *Syringodium filiforme* and *H. wrightii* are common in the northern bay, where salinities are lower and water clarity is diminished due to high freshwater discharge combined with a low flushing rate. Significant mixed *Thalassia/Syringodium* beds also exist in North Biscayne Bay. *Thalassia* is most prominent in central and south Biscayne Bay where salinities are higher and more stable and nutrient levels are lower overall.

The distribution of seagrass species and other benthic flora and fauna in the western nearshore area of central and southern Biscayne Bay is influenced by both canal discharges and submarine ground-water seepage (Kohout and Kolipinski 1967, Meeder et al. 1997, 1999). Presence or absence of *Thalassia* often is an indication of distinct zones where ground-water influence is substantial (*Thalassia* absent) or insignificant (*Thalassia* present). Along a transect from 25 to 300 m from shore, Meeder et al. (1997, 1999) found the maximum ground-water seepage about 200 meters from shore. The amount of ground-water seepage and its influence has been diminished by the general lowering of the water table in Miami-Dade County (Parker et al. 1955) to facilitate development in wetlands. Sea-level rise also reduced ground-water seepage to Biscayne Bay by reducing the hydraulic gradient, or difference between the water table and sea level at the coast, which, according to Darcy's Law, drives ground-water flow in an unconfined aquifer (Chow 1964).

Where sediment depths and currents are appropriate, seagrass species generally follow a pattern of zonation from west to east (*Ruppia*, *Halodule*, *Thalassia*, *Syringodium*) correlated with general salinity gradients

and salinity fluctuation (Lirman and Cropper 2003). The freshwater inflows (surface and ground) occurring along the shoreline are critical in maintaining this zonation and benthic diversity. The altered salinity patterns that resulted in concentration of surface-water inflows into canals and reduced ground-water seepage likely affected competition among seagrass species, changing this zonation and making it less defined. Results from a hydrodynamic simulation model comparing canal inflows versus distributed inflow indicate that the canal scenario produces higher overall salinity in the nearshore zone than the distributed inflows (i.e., to simulate flow through the historical creeks (Brown 2003). Channelization of the Miami River might have had a similar effect as construction of the South Miami-Dade canals that shortcircuited the historic creeks. Analysis of sediment cores from southern Biscayne Bay indicates that it has become more saline and less variable in the last 100–200 years (Wingard et al. 2003). Seagrass composition in these areas has been documented to vary between *Ruppia*, *Thalassia*, and *Halodule*, or mixtures of *Halodule* and *Ruppia* or *Halodule* and *Thalassia*, depending on salinity regime.

## Mangrove Functionality and Herbaceous Wetlands

Coastal wetlands are highly productive habitats that provide nursery, foraging, and refuge areas for many bird, fish, and invertebrate species. In addition, these coastal wetlands help maintain water and habitat quality by filtering sediments and nutrients from inflowing waters. Biscayne Bay's remaining mangroves and associated herbaceous wetlands, including nearshore freshwater wetlands, have lost much of their ecological function because fresh water has been diverted away from coastal feeder streams and creeks into drainage canals. Restoration of both brackish and freshwater wetlands and coastal creeks on the western shore of Biscayne Bay is important to the success of bay restoration and, therefore, is defined as an indicator of success. In the southern part of the western bay, water management and watershed development activities to date have caused saltwater intrusion and led to an encroachment of scrub mangroves on former freshwater wetland. Freshwater wetlands are a vital component of the coastal wetland system, and their loss is undesirable, even when replaced by salt-tolerant species like mangroves. The presence of a system of coastal wetlands integrated by the inflow of freshwater from upstream and, to varying degrees, by tidal exchange, is essential to the restoration of a fully functional Biscayne Bay ecosystem.

## Benthic Communities

Benthic organisms such as mollusks, attached fauna, and infauna provide essential ecological and biological functions in the bay and can influence the quality of the environment. The benthic community is the basis for development of high quality habitat that will support diverse fish and motile invertebrate populations. Degradation or loss of benthic communities will diminish the ability of the bay to maintain the mosaic of conditions that support high habitat diversity and productivity. Benthic communities are depauperate within the dredged canals and channels of the drainage system that empty into the bay. These channels provide poor habitat because of their depths, near vertical banks, low dissolved oxygen, and reduced water transparency (DERM 2005b). In addition, they are frequently redredged, disturbing the bottom sediments, and are regularly sprayed with herbicides. The present operation of water-control structures (opening and closing automatically according to upstream and downstream water level) causes discontinuous freshwater flows that result in localized extreme salinity variability that is unsuitable habitat even for estuarine organisms (Serafy *et al.* 1997).

## Pink Shrimp, Blue Crabs, Stone Crabs, and Oysters

Juvenile pink shrimp immigrate to Biscayne Bay from offshore spawning grounds each year and settle in the seagrass beds close to the mainland shoreline near freshwater inputs. Pink shrimp seem to prefer a salinity range of 20–35 parts per thousand (ppt) (Pattillo *et al.* 1997), but survival and growth have been tied to temperature and salinity (Browder *et al.* 1999), with an optimal salinity for juvenile growth at 30 ppt (Browder *et al.* 2002). This species would be expected to benefit from an expansion in estuarine habitat in the western bay. Pink shrimp's ecological characteristics and economic value, together with the background of knowledge about this species in South Florida, make it an appropriate biological indicator of change in freshwater inflow quantity, timing, and distribution. Furthermore, pink shrimp constitute the most significant commercial fishery in Biscayne Bay (Berkeley 1984). A commercial pink shrimp live-bait fishery has operated in Biscayne Bay for many years, and a more recent commercial fishery harvesting pink shrimp from the bay for human consumption is expanding. The distribution of juvenile pink shrimp in Biscayne Bay has been measured and modeled (Campos and Berkley 1986, Ault *et al.* 1999a, b). Spotted pink shrimp (*Farfantepenaeus brasiliensis* Latreille) also is present in Biscayne Bay but in very low number compared to *F. duorarum*).

The blue crab resides in the south-central area of Biscayne Bay and also supports a commercial fishery. An average of 50,768 kilograms of blue crabs was taken annually from Biscayne Bay from 1996 to 2000 (Murphy *et al.* 2001). Optimum blue crab egg hatching occurs at salinity between 23 ppt and 28 ppt, and juveniles prefer a seagrass habitat with salinity between 2 and 21 ppt (Pattillo *et al.* 1997).

The eastern or American oyster is not currently harvested in south-central Biscayne Bay but is present nearshore in small numbers where conditions are suitable. The species was apparently more abundant in the past when surface water drained through a series of small creeks into the bay (Meeder *et al.* 2001, 2002) and provided a salinity regime more conducive to oyster growth and survival. Growth rates of oysters are reported to be best at 14–28 ppt (Shumway 1996); however, at the higher salinity range, mortality can increase as a result of infection by *Perkinsus marinus* (Mackin, Owen, and Collier), a parasite (Burreson and Ragone-Calvo 1996, Soniat 1996, Chu and Volety 1997). The oyster is important ecologically for several reasons. The accumulation of shells provides physical habitat structure for a variety of other species, their organic rich deposits are a food source for benthic feeders, and they filter particulates from the water, improving water quality (Pattillo *et al.* 1997). Other estuarine species have some dependence on oyster reefs; for example, 24 species were found associated with oyster reefs in the Caloosahatchee Estuary (Volety *et al.* 2003).

## Estuarine Fish Communities

Several estuarine fish species known to have occurred in Biscayne Bay in the past (Smith 1896, Siebenaler 1953, Udey *et al.* 2002) contributed to the bay's commercial and recreational fisheries but appear to be scarce or absent in the bay today. The opportunity for anglers has changed and, according to long-time residents, has diminished, possibly as a result of the loss of the estuarine component of the fauna. The estuarine fish community could make an important contribution to the recreational fishing experience in the bay if its abundance and diversity were restored. An increase of the bay's estuarine habitat would be expected to lead to greater abundance and diversity of estuarine fishes, including those desired by anglers.

An increase in the distribution and abundance of fish in the fresh to brackish water wetlands adjacent to Biscayne Bay would be an indication of restored functionality of the coastal wetland-estuarine nearshore habitat that is important to the bay's diversity and productivity.

Freshwater fish communities that spread into oli-

gohaline (0–5 ppt salinity) environments seasonally can reach high densities and provide abundant prey to piscivorous estuarine fish, as well as to wading birds (Lorenz 2000).

#### Fish and Bottlenose Dolphin Health

The health of fish communities and the health of a resident bottlenose dolphin group are valuable attributes of the Biscayne Bay ecosystem. Externally visible abnormalities such as scale and skeletal deformities have been observed to occur in a number of Biscayne Bay fish (Browder et al. 1993) and are more prevalent in fish sampled from human-impacted sites (Gassman et al. 1994). This is consistent with Fournie et al. (1996) for Gulf of Mexico estuaries and Sanders et al. (1999) for Ohio rivers. The prevalence of abnormal fish is being used as part of a biological integrity index in a growing number of state and national monitoring programs (Simon 1999).

Bottlenose dolphins in Biscayne Bay include permanent residents and nearshore migrants. National Oceanic and Atmospheric Administration (NOAA) Fisheries conducts a photo identification program in Biscayne Bay that can potentially distinguish residents from migrants. Through the Southeast Fisheries Science Center, the NOAA Fisheries Miami Laboratory has been conducting health assessments of other bottlenose dolphin in the southeast to obtain baseline information on marine mammal contaminant levels, associated diseases and incidence, and impacts of human-related pollution on marine mammal populations. The program conducts current and retrospective evaluation for the accumulation of toxicants in various tissues of bottlenose dolphins and other marine mammal species in relation to their health, as reflected in histopathology, blood profiles, and other medical diagnostics (Sweeney 1992, Worthy 1992, Hansen and Wells 1996, Reddy et al. 2001, Schwacke et al. 2002). Biopsies of small amounts of subcutaneous blubber can be taken from living animals for contaminant analysis during low-level monitoring activities. Health assessment profiles of dolphin populations for comparison to regularly monitored and assessed “reference” populations can be developed in this manner. The bottlenose dolphin and other marine mammals are protected species under the Federal Marine Mammals Protection Act of 1972. Opportunistic biopsy sampling of the Biscayne Bay resident dolphin population began in February 2000 as a pilot study by the NOAA Fisheries Miami Laboratory.

#### Crocodile

The American crocodile is an endangered species that is known to range throughout southern Biscayne

Bay. Historically, the range of the American crocodile extended north to at least Miami Beach (Kushlan and Mazzotti 1989). It nests primarily at the Florida Power and Light Turkey Point Power Plant cooling canals and Crocodile Lake National Wildlife Refuge. Recent studies indicate an increase in the number of nests occurring in the cooling canal area of the Turkey Point Power Plant since the early 1980s, while nest numbers at the Crocodile Lake National Wildlife Refuge have remained relatively stable (Mazzotti et al. 2002). Nesting success at the Turkey Point Power Plant may be responsible for an increase in the number of crocodile sightings occurring north of the plant and may indicate an expansion of the animal's range. Crocodiles have been sighted as far north as Key Biscayne and the Miami River (M. Cherkiss, University of Florida, pers. comm.). Although nest numbers have remained relatively stable at the Crocodile Lake National Wildlife Refuge, the population in this area may be increasing, based on an increase in the number of crocodile sightings throughout the Florida Keys and an increase in the number of road kills occurring along U.S. 1 and Card Sound Road over the past several years (S. Klett, Crocodile Lake National Wildlife Refuge, pers. comm.).

A habitat suitability model for crocodiles has been developed based on salinity levels (Mazzotti and Brandt 1995). The model targets juvenile crocodiles because studies indicate that this life stage requires lower salinities due to osmoregulatory limitations (Mazzotti and Dunson 1984). This model shows that salinity between 0 and 20 ppt provides the most suitable habitat, 20–40 ppt provides intermediate suitability, and 40 ppt is least suitable. Applying the model to Biscayne Bay suggests that restoring freshwater flow to the coastal wetlands would benefit crocodiles, especially along the western shore in the central and southern regions. Most of this area is currently unsuitable for juvenile crocodile habitat. Restoration efforts will include redirecting flow from conveyance canals through coastal mangrove wetlands and maintaining flow into the beginning of the dry season.

#### Manatee

Endangered West Indian manatees occur throughout Biscayne Bay but are most frequently observed in tributaries and nearshore seagrass beds. Manatees are present year-round and are most abundant in winter, when more than 130 have been counted on a single day (Mayo and Markley 1995). Biscayne Bay seagrass meadows provide important foraging habitat for manatees wintering at warm water discharges (power plants) in Broward County, and the bay is a significant seasonal migratory corridor. Thus, the total number of



animals using the Biscayne Bay area is likely to be greater than the maximum number observed on any given day.

Manatees utilizing the bay are part of the larger Atlantic region “subpopulation,” which includes those animals ranging along the Atlantic coast from southern Georgia to the Florida Keys and including the lower St. John’s River. Atlantic coast manatees undertake seasonal, intraseasonal, and daily migrations or movements (Deutsch *et al.* 2003). Radio-telemetry studies and tracking or resighting of known scarred individuals have shown that manatees may travel hundreds of kilometers seasonally, moving to southeast Florida or unnatural sources of warmer water. Tracking studies of animals in the Biscayne Bay area also suggest a general diurnal pattern, with animals resting in canals and sheltered basins during the daytime and moving into bay areas to feed in late afternoon and evening (C. Beck, United States Geological Survey, pers. comm.). Although wide-ranging, manatees demonstrate a high degree of site fidelity, yet they also show individual patterns, flexibility, differential use of sites over time, and adaptation to changing conditions, moving among warm water refuges, freshwater sources, and feeding sites. The general distribution of manatees is strongly linked to fresh water; they more frequently occupy areas where freshwater sources are readily available (O’Shea and Kochman 1990, Mayo and Markley 1995, LeFebrve *et al.* 2001, Deutsch *et al.* 2003). Changes in timing and volume of freshwater delivery could affect manatee distribution, particularly in south Biscayne Bay.

Adult annual survival rates for manatees in the Atlantic subpopulation have been estimated at 88.7–92.6%, a lower rate than has been estimated for other regions (Langtimm *et al.* 1998). Due to uncertainty in population model estimations, it is not possible to determine with statistical confidence whether the Atlantic population has been stable, decreasing, or increasing in recent years; however, annual manatee mortality in the Atlantic region remains high and appears to be increasing at a greater rate than optimistic estimates of population growth (USFWS 2001). Although many manatees have been killed or injured in Biscayne Bay by vessel collisions, the leading known cause of manatee in death in Miami-Dade County is crushing or entrapment in water-control structures (Mayo and Markley 1995). Thus, changes in operation of these structures may directly affect survival of individuals using the Biscayne Bay area and stability of the Atlantic subpopulation.

#### Wading Birds

Wading birds are being used as biological indicators throughout the region because of their close associa-

tion with hydropattern. The islands, tidal flats, and coastal wetlands of Biscayne Bay provide valuable habitat for wading birds. Frequently used nesting sites occur at Greynold’s Park near the northern bay, in the Arsenicker Keys in the southern bay off Turkey Point, and on small islands off Key Biscayne and Virginia Key (Browder personal observation). Tidal flats and coastal wetlands of the bay provide important feeding habitat for wading birds that nest nearby. For example, roseate spoonbills (*Ajaia ajaja* Linnaeus) that nest in the Tern Keys of northeastern Florida Bay feed in mangrove creeks and herbaceous wetlands of southern Biscayne Bay (Card and Barnes Sound areas), as well as those of Florida Bay. Wood storks (*Mycteria americana* Linnaeus) that nest in the southern Everglades also feed in wetlands of southern Biscayne Bay. The natural pattern of seasonal variation in water stages alternately produces and concentrates forage fish for wading birds. A more natural seasonal variability in water stages in relation to the rainfall pattern will not only produce and concentrate fish for wading birds but also support favorable salinity conditions for estuarine fish and macroinvertebrates downstream in Biscayne Bay.

#### ECOLOGICAL EFFECTS: CRITICAL LINKAGES BETWEEN STRESSORS AND ATTRIBUTES/WORKING HYPOTHESES

In the Biscayne Bay Conceptual Ecological Model (Figure 2), relationships between the five stressors and the ecological attributes discussed above are depicted in the four diamond-shaped modules representing pathways of effects. Most of the ecological attributes are directly affected by salinity patterns/coastal wetlands, water quality, or sediment/water column contamination. These are determined by the stressors according to the relationships depicted in the “effects pathways” modules (the diamonds in Figure 2). The discussion of these effects pathways is followed by a discussion of hypothesized linkages between the ecological attributes and these effects pathways, including physical impacts (depicted in its own “effects pathways” module, fourth diamond in Figure 2). Physical impacts include effects of dredging, water-management control structures, and fishing gear.

#### Salinity Patterns/Coastal Wetlands

The ecological effects and interrelationships associated with salinity patterns and coastal wetlands are depicted in the third diamond in Figure 2. Data and historic accounts document that, in the past, freshwater inflows to Biscayne Bay were more diffuse and continuous via surface sheet flow, ground water, and



freshwater 'springs' within the bay (Kohout 1967, Kohout and Kolipinski 1967). These conditions generated a diverse salinity regime, with general gradients near 0 ppt close to the mainland, to 35 ppt or greater in the open areas of the bay in the southeast. These conditions apparently extended to Manatee Bay off Barnes Sound at the extreme southern end of Biscayne Bay (Ishman et al. 1998). Prior to drainage, several small rivers that flowed into the semi-enclosed northern part of the bay made it brackish. Natural patterns of salinity distribution and fluctuation were major determinants of habitat development, composition of biological communities within these habitats, and their overall productivity. Therefore, restoration of more natural freshwater inflows and associated salinity patterns and coastal wetlands are necessary prerequisites to restoration of the bay's natural estuarine diversity and productivity.

*Relationship between Salinity Patterns and Freshwater Inflows.* Both flow rate and distribution of freshwater inputs to Biscayne Bay have been altered by construction and operation of the present water-management system (Buchanan and Klein 1976). The system of canals and water-control structures provides a means to manipulate and control virtually all inflow to the bay. Altering the historical distribution of freshwater inflow in time and space has had an effect on patterns of salinity distribution and salinity variability. Routing freshwater flow to the bay through canals and away from coastal creeks and wetlands has resulted in a loss of estuarine habitat. The salinity gradient resulting from large, point-source discharges is very different from that resulting from more diffuse flow through tidal creeks and wetlands and ground-water seepage resulting from higher overall water tables. Inflows distributed through coastal wetlands resulted in a positive salinity gradient from interior wetlands and a broader mesohaline zone along the shoreline prior to drainage. Diversion of freshwater runoff into canals (i.e., point sources) short-circuits coastal wetlands and does not create positive gradients from interior wetlands outward. Although the general relationship between freshwater inflow and salinity is well known in Biscayne Bay, this relationship has not been rigorously quantified within the critical western nearshore zone and associated wetlands, where the greatest effect of changes in freshwater inflow patterns can be expected.

*Relationship between Freshwater Inflow and CERP.* Changes in upstream water-management practices will cause changes in freshwater inflow to Biscayne Bay. Modeling results with the South Florida Water Management Model (SFWMM) indicate that CERP's proposed changes to water-management features and practices in Biscayne Bay's watershed will

substantially affect freshwater delivery patterns. Exact relationships between rainfall in the watershed, freshwater delivery patterns, and planned changes to the water-management system are difficult to define quantitatively. For example, model estimates of daily discharge rates through coastal canal structures bear little relationship to daily rainfall, suggesting highly unnatural flow patterns. Furthermore, present methods of estimating discharge rates at structures can introduce significant error (Swain et al. 1997) and will need to be improved to fully investigate rainfall-runoff relationships.

### Water Quality

*Relationship of Biscayne Bay Water Quality to Water Quality in Ground Water, Storm Water, and Canal Discharge.* The term "water quality" includes both abiotic and biotic characteristics; therefore, water quality both influences and embodies major aspects of the ecological functioning of Biscayne Bay. The processes that link ecological attributes in Biscayne Bay to stressors are depicted in diamond 2 of Figure 2. In general, water clarity in Biscayne Bay is high, except where and when bottom sediments are disturbed by wave action or boat traffic. Inorganic nutrient concentrations are naturally low, and phytoplankton in the water column is not an impediment to light penetration. Open waters of Biscayne Bay are generally characterized by high dissolved oxygen concentration, low nutrient and chlorophyll concentrations, and high clarity. Sewage-related bacteria, trace metals, and other toxicants typically occur at low concentrations in Biscayne Bay waters. A primary controlling factor of water quality in Biscayne Bay is the quality of water discharged into the bay. Water quality in a number of canals and rivers that discharge to the bay is poor in comparison to the open waters of the bay. Surface waters in some canals in south Miami-Dade County that discharge into Biscayne Bay contain high levels of inorganic nitrogen.

Water quality can also be affected by ground-water inputs. In some areas, ground water contains elevated levels of ammonia nitrogen from landfill leachate and nitrate-nitrogen from agriculture (DERM 1987, Alleman 1990, Markley et al. 1990, DERM 1993, Alleman et al. 1995, Lietz 1999, Meeder and Boyer 2001). Submarine ground-water discharge into shallow nearshore waters is a source of elevated nutrients (Meeder et al. 1997); nutrient concentrations in shallow ground water (beneath the nearshore bay between Mowry Canal and Military Canal) are higher than in bay or canal waters or deep ground water. The structure and operation of water-management systems, land uses and urban and agricultural practices, and sea-level rise all affect

ground-water input (and nutrient loading) to Biscayne Bay.

Biscayne Bay is vulnerable to nutrient loading, especially from phosphorus, the limiting nutrient to phytoplankton growth in Biscayne Bay (Brand 1988). Water-column inorganic and organic nutrient concentrations, turbidity, photosynthetically-active radiation (PAR), bacteria, plankton taxa, size, and composition of plankton, as well as phytoplankton biomass, as reflected in chlorophyll and other pigments, can all be influenced by solids and nutrients received via canal discharge, stormwater runoff, and ground water.

CERP's proposed changes in freshwater delivery, particularly in south Miami-Dade County, may affect nutrient concentrations and loading to Biscayne Bay. On the one hand, plans to reroute canal discharge through coastal wetlands could reduce nutrients reaching Biscayne Bay; on the other hand, wastewater reuse may increase nutrient or other contaminant loading. While water-quality targets for wastewater reuse have been proposed that would protect open waters of south Biscayne Bay from degradation, it is not yet clear that achieving these targets is technically and economically feasible. This will pose problems since the water from wastewater reuse is a substantial part of total inflow to the bay provided under CERP (USACE and SFWMD 1999).

#### Sediment/Water Column Contamination

Processes linking ecological attributes to stressors are depicted in the first diamond in Figure 2. Community composition, distribution, and health of macrobenthic, infaunal, and demersal organisms can be affected by the presence of toxic substances in sediments. Potentially toxic pollutants, such as metals and organic chemicals, usually have low water solubility and tend to bind to particulate material and accumulate in sediments (Seal *et al.* 1994, Long *et al.* 2000). Most contaminants in Biscayne Bay sediments occur in highest concentrations in conveyance canals, rivers, streams, and marinas, and the lowest concentrations are along the central north-south axis of the bay (Corcoran *et al.* 1983, Alleman *et al.* 1995). Trace metals and synthetic organic contaminants, such as some pesticides and polychlorinated biphenyls (PCBs), are found in higher concentrations in Miami River and Wagner Creek sediments than in any other area in the State of Florida (Schmale 1991, DERM 1993, Seal *et al.* 1994). Other canals that have high levels of sediment toxicity include Little River (C-7), Black Creek (C-1), and Military Canal (USEPA 1999, Miami-Dade County Department of Environmental Resource Management, pers. comm.).

*Relationship of Sediment/Water Column Concentration to Toxicity.* Recent studies (Long *et al.* 2000, 2002) showed that contaminant levels in Biscayne Bay sediments were slightly below the national average, but toxicity levels (based on biological assays) were slightly above. These studies supported earlier findings that contamination and toxicity were most severe in several conveyance canals and a few natural tributaries, and that sediments from the open basins were less toxic than those from the adjoining canals and tributaries. In more open waters of the bay, chemical concentrations and toxicity were generally higher north of Rickenbacker Causeway than south of it. However, a section of southern Biscayne Bay showed remarkably high toxicity that could not be attributed to any of the substances analyzed in sediments. Evidence suggests that mixtures of some metals and synthetic organic chemicals were likely contributors to toxicity observed in the lower Miami River. For example, an amphipod survival test showed a high degree of correspondence with a gradient of general chemical contamination in the river and adjoining reaches of the bay. Because contaminants are conveyed to the bay through tributaries and ground-water flux, changes in distribution or sources of fresh water or ground-water stages may affect the fate, amount, and pattern of contaminants introduced. This could increase water-column and sediment contaminant levels (or toxicity), increase ecological exposure, and ultimately affect sensitive species and, perhaps, overall secondary productivity or diversity.

#### Seagrass Habitat

*Relationship of Seagrass Abundance and Distribution to Salinity Patterns and Water Quality.* Processes linking the bay's ecological attributes to stressors are depicted in the second diamond in Figure 2. Seagrass and benthic communities require a consistent (both in range and variability) salinity regime and appropriate water quality (sufficient but not excessive nutrients and sufficient light for photosynthesis). Abundance, distribution, and composition of seagrasses will be determined, in part, by modifications of salinity patterns and water quality. Changes in composition and areal coverage of seagrasses will affect habitat quantity and quality with respect to breeding, refuge, and feeding areas available for dependant invertebrate and vertebrate species. Diversion of part of the canal flow from a 'point source' to more 'diffuse' delivery through coastal wetlands and creeks will approximate reconstruction of freshwater flow to the bay from the Everglades through historic pathways (i.e., the historic freshwater coastal creeks, as many as 40 of which interdigitated with tidal creeks prior to development).

This is expected to reduce sediment resuspension and nutrient concentrations in the water delivered to the bay and improve water clarity. This could lead to expansion of seagrass cover in the nearshore areas where sediment depths are adequate and may improve local water clarity by inhibiting sediment resuspension.

#### Mangrove Functionality and Herbaceous Wetlands

*Relationship of Freshwater Inflow and the Boundary between Mangrove and Herbaceous Wetlands.* The relationship of mangrove functionality to stressors is depicted in the third diamond of Figure 2. Diversion or reduction of freshwater inflow has caused a loss of the many small creeks that furnished freshwater to the bay and has diminished the degree to which mangroves support a healthy, diverse epiphytic community and provide habitat for both sport fish and their prey. Alteration of freshwater inflow has caused a shift in the boundary between the mangrove and herbaceous wetland and the inland migration of the landward boundary of the "white zone" (Ross et al. 2000). The white zone is a band of low productivity at the ecotone between brackish and freshwater wetlands. Recent studies in the wetlands of Barnes and Card Sounds (see Figure 1 for location) indicate that the boundary of the white zone has moved inland by an average of 1.5 km since 1940, and the white zone is expanding (Ross et al. 2000). The most significant changes to the white zone boundary and width occur in areas cut off from freshwater sources by canals or roads (especially east of U.S. Highway 1). Low productivity of the white zone may be primarily the result of wide seasonal fluctuations in soil salinity and moisture content due to reductions in freshwater inputs from upstream sources (Ross et al. 2002). CERP's restoration of a more natural freshwater flow across the coastal wetlands should reduce the areal extent of the white zone and shift its inland boundary seaward. Reestablishing flow across a broader front through re-created coastal freshwater creek systems should also restore full mangrove functionality. Exotic vegetation has replaced the white zone in some areas but is not a substitute for natural herbaceous wetland, and the exotics may have to be addressed with specific remedies to restore coastal wetlands.

Sea-level rise has to be considered in wetland restoration. For one, it influences the location of the ecotone between the mangrove and herbaceous wetland and the boundary of the white zone, and sea-level rise might shift them inland over coming decades. For another, hydrostatic pressure from increased sea level might further retard ground-water inflows already diminished by a lowered water table.

#### Benthic Communities

*Relationship of Bottom Habitat to Freshwater Inflow Volume and Variation.* Benthic communities are related to stressors as depicted in the third diamond of Figure 2. Benthic communities are directly impacted by the volume and intensity of freshwater inflow and the range and rapidity of its variation. Point-source discharges of fresh water into the bay via conveyance canals result in large, but ephemeral, salinity fluctuations that deleteriously affect benthic communities (Montague and Ley 1993, Irlandi et al. 1997). The bay bottom in the vicinity of canals often is devoid of benthic organisms. Miami-Dade Department of Environmental Resources Management documented destruction of established benthic sessile communities in Manatee Bay in the extreme south Biscayne Bay by sudden and prolonged high-volume releases of fresh water. Recovery is dependent upon the duration of appropriate salinity regimes between events. Benthic communities are also directly affected by trawling, which can significantly disturb bottom habitat and benthic organisms.

#### Pink Shrimp

Pink shrimp are related to stressors primarily through diamonds 2 and 3 in Figure 2. These relate suitability of habitat for pink shrimp to salinity pattern and water quality and catches in the fishery to abundance of juvenile pink shrimp.

*Relationship of Suitable Pink Shrimp Habitat to Salinity Pattern and Water Quality.* Changes in water management in relation to CERP are expected to expand the area of optimal habitat for juvenile pink shrimp both directly and indirectly. Salinity, which affects many physiological processes, is a major environmental factor directly influencing pink shrimp. Like many species, pink shrimp have an optimum salinity range (Browder et al. 2002). Although the species may be found outside of this range, survival, growth, and reproduction may not be as great. As for many species, optimum salinity for shrimp must occur in conjunction with suitable bottom habitat (e.g., seagrass) to be supportive, and salinity patterns and water quality will directly affect seagrass distribution, composition and density, thus affecting shrimp indirectly (Browder et al. 2005).

*Relationship of Juvenile Pink Shrimp to Shrimp Harvests.* High densities of juvenile pink shrimp can be expected to enable high catch rates in fisheries. A close link between juvenile densities and catch rates in bay shrimp fisheries would be expected because nursery and fishing grounds overlap or are in close proximity.



Fishing effort may affect juvenile density on fishing grounds, but trawls cannot operate in waters less than one meter deep, where the nursery grounds in Biscayne Bay are located (Diaz 2001). The relationship of pink shrimp juveniles in Biscayne Bay to offshore spawning or fishing grounds is unknown. The nearest known spawning and fishing grounds are near the Dry Tortugas, and the relationship between the spawning grounds and the Biscayne Bay nursery has not been determined.

### Estuarine Fish Community

*Relationship of Estuarine Fish Communities to Salinity Pattern.* The estuarine fish community is related to stressors through diamonds 2 and 3 in Figure 2. Abundance and biomass of estuarine fishes has been reduced and species diversity has changed due to a loss of estuarine habitat along the bay's western shoreline (Serafy *et al.* 2001). Much of this habitat loss stems from changes in freshwater inflow that have disturbed the natural correspondence of favorable salinity with favorable bottom and shoreline habitat for estuarine species (Browder and Moore 1981). These species need a persistent positive salinity gradient extending from coastal wetlands, freshwater coastal creeks, and shallow nearshore waters into the bay. Flow from canals rather than through coastal wetlands prevents development of a positive gradient from interior wetlands into the bay. Unnaturally high salinity fluctuations caused by canal discharges further reduce suitable habitat for estuarine fish communities (Serafy *et al.* 1997). Presently, the rate of freshwater inflow fluctuates in a much more pronounced way than it did prior to the construction of the water-management system. Fluctuation is because of the shortage of storage for stormwater runoff in the watershed and manipulation of the little storage that exists. For example, at the end of wet season and during dry season (generally November to May), water may be discharged to artificially maintain low ground-water elevations in the watershed to promote agricultural activity, even though no rainfall has occurred; contrarily, sometimes no water is discharged after storm events because water stages are still below optimum. Spatial and temporal patterns of freshwater delivery that radically depart from the natural pattern of flow in relation to rainfall do not provide optimal habitat for estuarine species. Many species that can withstand gradual changes in salinity are vulnerable to the abrupt lowering of salinity caused by freshwater pulses (Serafy *et al.* 1997).

### Fish and Bottlenose Dolphin Health

Contaminants present in Biscayne Bay's sediments and water column at various locations, including the Miami River mouth, may affect faunal health and development in the bay. Fish and bottlenose dolphin were selected to help monitor potential adverse effects of contaminants because a relatively high prevalence of morphological abnormalities has been found in fish from some locations in Biscayne Bay, and bottlenose dolphin are a long-lived species in which contaminants are known to accumulate, according to studies in other estuaries. Fish and dolphin health are related to stressors through diamond 1 in Figure 2.

*Relationship of Fish Abnormalities to Human Influences.* The relationship between exposure to anthropogenic inputs and morphological abnormalities observed in Biscayne Bay fishes needs evaluation in view of the higher prevalence of fish with abnormalities in areas of the bay directly exposed to human inputs. The most common abnormalities in Biscayne Bay fish are scale disorientation and deformed or missing dorsal fin spines, which are found in a number of species (Browder *et al.* 1993). Limited data from selected locations showed significant correlations between combined abnormalities and aliphatic hydrocarbons in sediments and between abnormalities in bluestriped grunt (*Hemulon sciurus* Shaw) and copper in sediments (although not with other sediment contaminants) (Gassman *et al.* 1994). Other factors can also influence fish health and development, including, according to some reports, previous encounters with fishing gear.

*Relationship of Bottlenose Dolphin Toxicant Body Burden to Toxicants in the Sediments.* The body burden of toxicants in the Biscayne Bay resident bottlenose dolphin population may reflect their degree of toxicant exposure. Body burdens could be correlated with various health-assessment indices that describe the status of population health. Through NOAA and its collaborators, a program is gradually evolving that characterizes toxicant body burdens and blood profiles of dolphin populations in various estuaries of the southeastern United States. Information from the resident Biscayne Bay dolphin population could therefore be used to compare toxicant exposures in Biscayne Bay to other estuaries. Such an effort would be facilitated by the ongoing NOAA project to identify and catalogue resident dolphins of the bay to distinguish them from members of coastal migrant populations and to determine local movements.

### Manatees

The relationship of manatees to stressors is depicted in diamonds 3 and 4 of Figure 2. Manatees are directly

affected by floodgate closures, a documented cause of mortality. They may also be affected by the way that canals and levees have concentrated the availability of fresh water at a few sites, almost all near floodgates.

*Relationship of Manatee Distribution to Timing, Location, and Volume of Freshwater Inflow.* Changes in timing, location, and volume of freshwater inflow could affect manatee distribution within the bay and their use of canal habitat. For example, restoration of more natural and stable freshwater creeks and springs may enhance manatee habitat in areas more remote from human threats. However, complete elimination of existing canals (or access to them) or discharge structures may disrupt behavior of individual manatees that traditionally utilize such sites.

*Relationship of Manatee Mortality to Water-Control Structure Operations.* Water control floodgates are the leading cause of determinable manatee mortalities in Biscayne Bay (Mayo and Markley 1995, FWC 1999, USFWS 2001). Miami-Dade County leads the state in floodgate and other human-related causes of manatee mortality. Manatees are attracted to canals as a source of fresh water and cold-weather refuge. Over the last two decades, water-control-structure operations have been modified, and some gates have been retrofitted with pressure-sensitive devices that are supposed to prevent the gates from closing on an object. Although this has resulted in some improvement, mortalities have continued. Modification of gates or their operation may affect manatee mortality. For example, if water normally discharged through a coastal water-control gate were diverted into a series of creeks, as planned in the Biscayne Bay Coastal Wetlands Project of CERP, then the frequency that the gate opens and closes would be reduced, thereby reducing the risk to manatees. The number of manatees in Biscayne Bay increases during cold weather, increasing vulnerability to human related impacts (e.g., control structures and boats) during that time of year, so gate operations are particularly important then.

#### Wading Birds

*Relationship of Wading Bird Nesting Activity, Nesting Success and Foraging Activity to Water-Management Structures and Their Management.* The relationship of wading birds to stressors is primarily through effects expressed in diamond 3 of Figure 2. Lorenz (2001a,b) showed that nesting success of roseate spoonbills in one colony (Tern Key) was detrimentally affected by changes in water stages caused by water-management structures and operations near Florida Bay. Feeding opportunities for roseate spoonbills and other wading birds also have been diminished by the

reduction in freshwater flow to Biscayne Bay wetlands resulting from road construction and diversion of water into canals. Modification of the structure and operation of the water-management system in relation to Biscayne Bay wetlands could affect nesting success at the Tern Key site in eastern Florida Bay. Improvements in water management might also affect activity and nesting success of colonies of wading birds that nest on islands within Biscayne Bay.

#### RESEARCH QUESTIONS

Science issues were identified based on the hypotheses encapsulated in the conceptual ecological model. Those considered most important to address before restoration construction plans are finalized were consolidated into a set of 14 research questions. The selection of the most important science issues was by informal consensus in the workshops organized to develop the model and was based primarily on the degree to which the topic was considered to be fundamental to the success of Biscayne Bay restoration and relative uncertainty. The following 14 research questions, roughly prioritized by the authors, were identified.

1. What is the quantitative relationship between upstream water management, rainfall, and flow into Biscayne Bay?
2. How is estuarine habitat affected by quantity, timing, and distribution of freshwater inflow?
3. What salinity gradient from interior coastal wetlands through the nearshore zone would optimize diversity and abundance of oligotrophic and mesohaline fish species in the bay and its coastal wetlands?
4. What is the quantitative relationship between nutrient and contaminant loads and spatial and temporal patterns of water-quality and sediment-quality?
5. Will use of reclaimed wastewater as a significant component of freshwater inflow have ecological, water quality, or sediment quality effects?
6. How is juvenile pink shrimp abundance affected by changes in quantity, timing, and distribution of freshwater inflow, and is there a direct quantitative relationship between juvenile pink shrimp abundance and fishing success? Is the catch per unit of effort in these fisheries affected by freshwater inflow?
7. How might proposed changes in water management affect seagrass distribution, density, species composition, and dominance in the western nearshore area?
8. What are the effects of freshwater inflow change and sea-level rise on the white zone?
9. What is the functional relationship of toxicant concentrations and fish exposure to the types of abnormalities prevalent in Biscayne Bay fish?
10. What is the actual exposure to toxicants of the bottlenose dolphins in Biscayne Bay?
11. Will changes in freshwater volume and delivery affect manatee distribution, particularly in south Biscayne Bay?
12. What effects will changes in

water management and control structures have on manatee mortality in Biscayne Bay. 13. Will wading bird nesting activity, nesting success, and foraging activity be improved by the reestablishment of more natural hydropatterns in Biscayne Bay's coastal wetlands? 14. Will changes in water management affect the spread of exotic fish and macroinvertebrate species?

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